

NGC 2419: a large and extreme second generation in a currently undisturbed cluster

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ABSTRACT

We analyse complementary HST and SUBARU data for the globular cluster NGC 2419. We make a detailed analysis of the horizontal branch (HB), that appears composed by two main groups of stars: the luminous blue HB stars —that extend by evolution into the RR Lyrae and red HB region— and a fainter, extremely blue population. We examine the possible models for this latter group and conclude that a plausible explanation is that they correspond to a significant ($\sim 30\%$) extreme second generation with a strong helium enhancement ($Y \sim 0.4$). We also show that the color dispersion of the red giant branch is consistent with this hypothesis, while the main sequence data are compatible with it, although the large observational error blurs the possible underlying splitting.

While it is common to find an even larger (50 – 80) percentage of second generation in a globular cluster, the presence of a substantial and extreme fraction of these stars in NGC 2419 might be surprising, as the cluster is at present well inside the radius beyond which the galactic tidal field would be dominant. If a similar situation had been present in the first stages of the cluster life, the cluster would have retained its initial mass, and the percentage of second generation stars should have been quite small (up to $\sim 10\%$). Such a large fraction of extreme second generation stars implies that the system must have been initially much more massive and in different dynamical conditions than today. We discuss this issue in the light of existing models of the formation of multiple populations in globular clusters.

Key words: globular clusters: general; globular clusters: individual: NGC 2419; stars: abundances

1 INTRODUCTION

Most globular clusters (GC) so far spectroscopically examined have been shown to contain multiple stellar populations. Together with stars having the typical composition of halo stars of the same metallicity, they contain a population of stars whose gas has been subject to the full CNO cycle (decrease of the oxygen content) and to proton–capture reactions on light nuclei (e.g. formation of sodium from neon). Taking as a probe the Na–O anticorrelation, Carretta et al. (2009a) show that all the 19 galactic GCs they examine display it. As the chemical signatures of the anomalies are

present also in turnoff (TO) stars and among the subgiants (e.g. Gratton et al. 2001; Briley et al. 2002, 2004), they can not be attributed to “in situ” mixing in the stars, but must be due to some process of self–enrichment occurring during the first stages of the cluster life.

Photometric evidence for the presence of multiple populations are also numerous, and sometimes suggestive of star formation occurring in successive bursts. The photometric signatures can be attributed in part to helium differences (morphologies of the horizontal branches (HB), multiple main sequences) or sometimes even to merging of different initial cluster-like structures (Carretta et al. 2010).

Different models have been discussed in the literature for the formation of multiple stellar populations. A general feature is that, apart from some exceptions, the iron content of normal and anomalous stars does not differ significantly (according to Carretta et al. 2009c, the iron spread in most GCs is contained within $\sim 0.05\text{dex}$). The gas having the chemical signatures of second generation (SG) stars must have been at least partially nucleary processed in stars of the first stellar generation (FG) and it does not include supernova ejecta.

A major problem is the following: both the interpretation of the HB morphologies in terms of helium enrichment, and the spectroscopic information show that, in the clusters so far examined, the percentage of stars of the SG is generally $\sim 50\text{--}80\%$ (D’Antona & Caloi 2008; Carretta et al. 2009a). Such a large fraction of SG stars can not be the result of chemical evolution within a “closed box”, simply because the processed matter available from more massive stars is always a small percentage of the FG mass. Anomalous IMFs of the FG do not solve the problem, instead it is required that the matter forming the SG stars is collected from a much larger stellar ensemble than what can be inferred by extrapolating to larger masses the present day mass function of FG stars. Possible models imply that either the GC has formed in the environment of a dwarf galaxy now dispersed (e.g. Bekki & Norris 2006), or the SG has formed in the core of a much more massive FG cluster, filling its tidal volume and losing about 90% of its initial mass (D’Ercole et al. 2008) in the first phases of its dynamical evolution. In all cases, a multiple-generation cluster is today believed to be ‘small’ remnant of the evolution of a stellar system initially much more massive (see also Vesperini et al. 2010 for a study of the cluster properties required for the formation of a significant SG population and the implications for the contribution of globular clusters to the Galactic halo assembly).

Important clues to understand the GC formation might come from the analysis of the stellar content of GCs that evolved in isolation since their formation and did not undergo any significant loss of stars that altered the initial relative numbers of FG and SG stars. In this work, we examine NGC 2419, one of the most massive galactic GCs. The cluster core relaxation timescale is $\sim 10^{10}\text{yr}$, while the half mass relaxation time is much longer than the Hubble time (Harris 1996, 2010 edition). It is very distant ($\sim 87.5\text{kpc}$ according to Di Criscienzo et al. 2011), its present truncation radius is $8.74'$ ($\sim 220\text{pc}$) according to Trager et al. (1995), while its tidal (Jacobi) radius is $\sim 700\text{pc}$ (see Sect.7). Had this cluster evolved in its current environment since its formation, it might have retained memory of the conditions imprinted by the formation processes. On the other hand, NGC 2419 has a very extended HB morphology, with the presence of a well populated blue hook, generally regarded as a sign of the presence of an extreme, helium rich population (e.g. Lee et al. 2005; D’Antona et al. 2002).

We take advantage of two rich HST and SUBARU observational samples, discussed in Section 2, and of new models computed on purpose for this work (Section 3) to make a detailed analysis of the HB population (Section 4), of the giant branch (Section 5) and of the main sequence (Section 6). We find several compelling reasons to suggest that this cluster contains two stellar generations, with a very helium rich SG comprising $\sim 30\%$ of the cluster present population.

In Section 7 we discuss this result, and what it implies for the formation and dynamical history of this cluster.

2 OBSERVATIONAL DATA SAMPLES

The observations consist in three different data sets including the Hubble Space Telescope (*HST*) images described in Sect. 2.1.1, and ground-based images taken with the SUBARU telescopes and described in Sect. 2.2. The main properties of these images are listed in Table. 2.1.

2.1 The *HST* data set

To analyse the ACS/WFC images we followed the recipes described in Anderson et al. (2008). We used a software that analyses all the exposures simultaneously and generates a single list of stars. Stars are measured independently in each image by using a spatially varying 9×10 array of empirical “library point-spread functions (PSFs)” from Anderson & King (2006), plus a spatially constant perturbation for each exposure that accounts for variations in the telescope focus.

The software was designed to work well both in the crowded central regions of the cluster and in the external uncrowded field and is able to measure almost all the stars that would be detected by eye. The photometry was calibrated into the ACS Vega-mag system by adopting the zero points given in Sirianni et al. (2005) and following the procedure by Bedin et al. (2005). To exclude stars that are poorly measured we followed the selection procedures given in Milone et al. (2009) and included in the analysis only relatively isolated, unsaturated stars with good values of the PSF-fit quality index and small rms errors in photometry and in astrometry.

Breathing can change the focus of the telescope and introduce small spatial variations of the PSF, which is not compensated for in our PSF model and can result in small spatial variations of the photometric zero point. To minimize the effect of any residual PSF variation on the photometry we used the method adopted by Milone et al. (2010). Briefly, we first determine the fiducial main sequence for the cluster and compute for each star its color residual from it. Then, we correct the star’s color by the difference between its color residual and the mean of those of its best-measured neighbors. The spatially dependent correction was lower of 0.005 mag, and accounts for both differential reddening and inaccuracies in the PSF model, regardless of the cause. The above procedure works well also in the case of a spread out MS, or even of a double or multimodal MS as shown for example in Milone et al. (2010), where this same technique was applied to the double MS in NGC 6752.

2.1.1 Artificial stars

The artificial-star (AS) experiments which have been used in this paper are also fully described in Anderson et al. (2008). Briefly, for each cluster, we generated a list of 10^5 stars located on the entire ACS field of view, with a density that is flat within the core and declines as r^{-1} outside of the core. The programs described in Anderson et al. (2008) allow ASs test to be performed for one star at a time and

DATE	N×EXPTIME	FILT	INSTRUMENT	PROGRAM
Sep 25 2002	2×400s	F435W	ACS/WFC	9666
Sep 25 2002	2×340s	F475W	ACS/WFC	9666
Sep 25 2002	2×360s	F555W	ACS/WFC	9666
Sep 25 2002	2×338s	F606W	ACS/WFC	9666
Sep 25 2002	2×340s	F775W	ACS/WFC	9666
Sep 25 2002	2×338s	F814W	ACS/WFC	9666
Sep 25 2002	3×340s	F50LP	ACS/WFC	9666
Dec 2002(4nights)	165×30/180s	V	SuprimeCam/SUBARU	-
Dec 2002(4nights)	16×30/180s	I	SuprimeCam/SUBARU	-

Table 1. Description of the archive data sets used in this paper.

entirely in the software: following this procedure, artificial stars never interfere with each other. The ASs have a flat luminosity function in F606W, instrumental magnitudes from -5 to -14 and colors that place them along the horizontal branch.¹

The AS routine measures the images with the same procedure used for real stars. We considered an artificial star as recovered when the input and the output fluxes differ by less than 0.75 magnitudes and the positions by less than 0.5 pixel and applied to the AS catalog the same criteria of selection adopted for real stars.

Since completeness depends on crowding as well as on stellar luminosity, we measured it applying the procedure described in Milone et al. (2009) that accounts for both the stellar magnitude and the distance from the cluster center. Briefly we divided the ACS field into 7 concentric annuli and, within each of them, we examined AS results in 9 magnitude bins, in the interval $-14 < m_{F814W} < -5$. For each of these 9×7 grid points we calculated the completeness as the ratio of recovered to added stars within that range of radius and magnitude. This grid allowed us to estimate the completeness associated to any star at any position within the cluster. This completeness analysis is used in Section 4.2 to derive the relative percentage of stars on HB.

2.2 The ground-based data set

Ripepi et al. (2007), using three different data set (SUBARU, TNG and HST) published a CMD of NGC 2419 which, for the first time, is both deep and covers a very large field of view around the cluster. In particular the large field of view of the Suprime-Cam (34×27 arcmin²), covered by a mosaic of 10 CCDs and by dithering of the telescope pointings, resulted in the survey of a total area of 50×43 arcmin² centered on NGC 2419 and include both the TNG and HST fields. In the SUBARU data, the cluster is centered on chip #2 and it is totally covered by the five adjacent chips; the data consist of 30s and 180s exposures in both the *I* and *V* bands. The techniques used to perform both the PSF photometry and the absolute calibration are described in detail in Di Criscienzo et al. (2011). The samples cover a total range of about 9 magnitudes, from the tip of the cluster red giant branch (RGB) around $V \sim 17$ mag, down to $V \sim 25.7$ mag, about 2.3 mag below the TO, and extend

over an area encompassing more than 1 tidal radius in the North-South direction and about 2 tidal radii in East-West from the cluster center. We have not included in the catalogue stars lying at $r < 50''$ to avoid incompleteness effects in the most crowded central regions. The consequence of this conservative choice is that the typical internal errors of the *V* band photometry at the level of the HB are from 0.01 to 0.02 mag. The CMD by Ripepi et al. (2007) shows that the HB of NGC 2419 extends down to an extremely long blue tail ending with a “blue hook” (Whitney et al. 1998; D’Cruz et al. 2000).

In addition on the same data set, Di Criscienzo et al. (2011) have detected 101 variable stars of which 60 new variables. According to their study NGC 2419 contains 75 RR Lyrae stars, 40 of which are located at $r > 50''$. These observations complete the data for the brighter part of the HB, allowing an analysis through population synthesis². We found that 42 of the total number of RR Lyrae stars found in NGC2419 by Di Criscienzo et al. 2011 are in the ACS field described in the previous section. This allows us to complete with the variables the ACS catalogue described in Section 2.1 for the upper part of the HB.

3 THE MODELS

We computed several sets of isochrones and HB evolutions. Based on the paper by Shetrone et al. (2001), we choose as our base composition a mixture with $[\text{Fe}/\text{H}] = -2.4$ and $[\alpha/\text{Fe}] = 0.2$ (standard). We also provide a set of models for the same iron content and $[\alpha/\text{Fe}] = 0.4$ ($\alpha 04$). More recent results by Cohen et al. (2010) shift this value in the range $[\text{Fe}/\text{H}]$ from ~ -2 to ~ -2.2 . We will see that the global interpretation of the cluster data is not affected by the exact choice of metallicity, but a slightly larger iron content is probably more adequate to understand the whole horizontal branch data (Sect. 4.2).

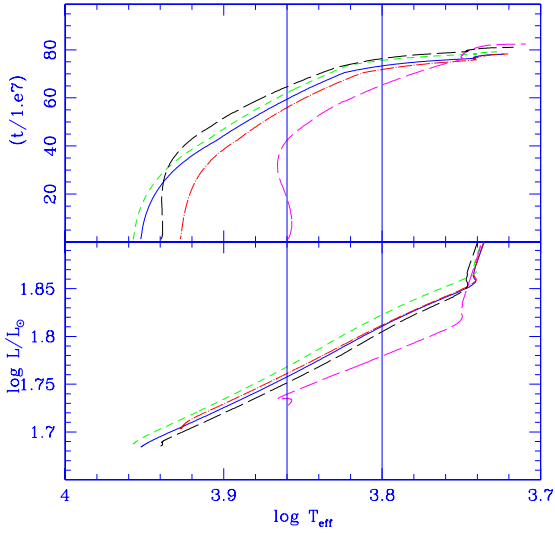
For $T > 10000\text{K}$ we used the OPAL opacities, in the version documented by Iglesias & Rogers (1996), with all the recent updates; at lower temperatures the opacities by Ferguson et al. (2005) were adopted. Conductive opacities were taken from Poteckhin (2006, see the WEB page www.ioffe.rssi.ru/astro/conduct). We adopt the new cross section for the reaction $^{14}\text{N} + \text{p}$ (Formicola et al. 2004), but provide a set of models also for the old cross

¹ The instrumental magnitude is calculated as $-2.5 \log(\text{DN})$, where DN is the total digital counts above the local sky for the considered stars

² On the contrary the SUBARU data for the “blue hook” are largely incomplete and will not be used.

Table 2. HB models and isochrones

Name	Z	[Fe/H]	$^{14}\text{N}+\text{p}$	$[\alpha/\text{Fe}]$	Y -HB	Y -Isochrones	$M_{\text{core}}/M_{\odot}$
Standard	10^{-4}	-2.4	new	0.2	0.24	0.24	0.505
					0.28	0.28	0.499
					0.42	0.35	0.466
					0.7, 0.8, 0.9	0.42	$\geq 0.450, \leq 0.465$
OLDN14	10^{-4}	-2.4	old	0.2	0.24		
$\alpha 04$	10^{-4}	-2.55	new	0.4	0.25		
D2002	2×10^{-4}	-2.0	old	0.0	0.24	0.24	0.508
					0.28	0.28	0.497

**Figure 1.** Top panel: time evolution as function of T_{eff} ; bottom panel: HR diagram location of HB tracks of $0.74 M_{\odot}$ for different assumptions. Full line (blue): “standard” track with $[\text{Fe}/\text{H}]=-2.4$ $[\alpha/\text{Fe}]=0.2$; dot-dashed (red): OLDN14; short dashed (green): $\alpha 04$; long-dashed (magenta): $0.74 M_{\odot}$ from D2002. The other long-dashed track on the left (black) is the $0.70 M_{\odot}$ from D2002.

section (Angulo et al. 1999). Finally, some comparisons with the data are also made with the previous models described in D’Antona et al. (2002) (hereinafter D2002) and D’Antona & Caloi (2008) computed for a metallicity $Z=2 \times 10^{-4}$, and no α enhancement. The description of the main inputs and of the corresponding models are given in Table 2.

We followed the main sequence and red giant evolution of low mass tracks to provide isochrones for the chosen chemistry and the helium core mass at flash for each set. The red giant evolution was followed by adopting the Reimers’ (1975) mass loss law, with the Reimers parameter fixed to $\eta=0.3$. These core masses are also given in Table 2, and are taken as input for the computation of the HB models. The small helium increase in the envelope during the red giant evolution is also taken into account in the HB models. Further HB models were computed, with reduced helium core mass, in order to simulate the effect of late flash mixing. Models of low total mass ($M < 0.5 M_{\odot}$), for envelope helium $Y=0.7, 0.8$ and 0.9 were added to the main HB mass sets.

Models include non instantaneous mixing of the chemicals species within the convection zones. We follow the diffusive approach by Cloutman & Eoll (1976), solving for each chemical species the diffusive-like equation:

$$\frac{dX_i}{dt} = \left(\frac{\partial X_i}{\partial t} \right)_{\text{nucl}} + \frac{\partial}{\partial m_r} \left[(4\pi r^2 \rho)^2 D \frac{\partial X_i}{\partial m_r} \right] \quad (1)$$

where D is the diffusion coefficient, for which, given the convective velocity v and the scale of mixing l , a local approximation ($D \sim \frac{1}{3}vl$) is adopted. The borders of the convective regions are fixed according to the Schwarzschild criterion. We include extra-mixing from all the formal convective boundaries up to the beginning of the AGB phase: convective velocities are assumed to decay exponentially with an e-folding distance described by the free-parameter ζ , that was set to $\zeta = 0.02$, according to the calibration provided in Ventura et al. (1998), where the interested reader can also find a complete discussion regarding the variation of the convective velocities in the proximities of the convective borders. The treatment of overshooting is particularly relevant for the HB models, in which overshooting mimicks semi-convection (e.g. Caloi & Mazzitelli 1990).

The models with $Z=10^{-4}$ and $Y=0.24$ give an evolving mass of $0.740 \pm 0.008 M_{\odot}$ to fit the location of the upper HB. Therefore we compare in Fig. 1 the evolutionary tracks for this mass and different inputs. The biggest difference is that the old D2002 tracks, corresponding to $Z=2 \times 10^{-4}$ and no α enhancement, are considerably cooler than the standard tracks. The best correspondence is found between the standard $0.74 M_{\odot}$ track and a track of $0.70 M_{\odot}$, also plotted in the figure. Doubling $[\alpha/\text{Fe}]$, but leaving the total metallicity unchanged, we find that the track of $0.74 M_{\odot}$ is only slightly cooler and more luminous. On the other hand, the $^{14}\text{N}+\text{p}$ cross section does not look to be particularly relevant for this metallicity (but see also Ventura et al. 2009; Pietrinferni et al. 2010).

Synthetic models for the HB are computed according to the recipes described in D’Antona & Caloi (2008). We adopt the appropriate relation between the mass of the evolving giant M_{RG} and the age, as function of helium content and metallicity. The mass on the HB is then:

$$M_{\text{HB}} = M_{\text{RG}}(Y, Z) - \Delta M \quad (1)$$

ΔM is the mass lost during the RG phase. We assume that ΔM has a gaussian dispersion σ around an average value ΔM_0 and that both ΔM_0 and σ are parameters to be determined and *in principle* do not depend on Y . Once chosen Z and Y , the T_{eff} location of an HB mass is fixed. Con-

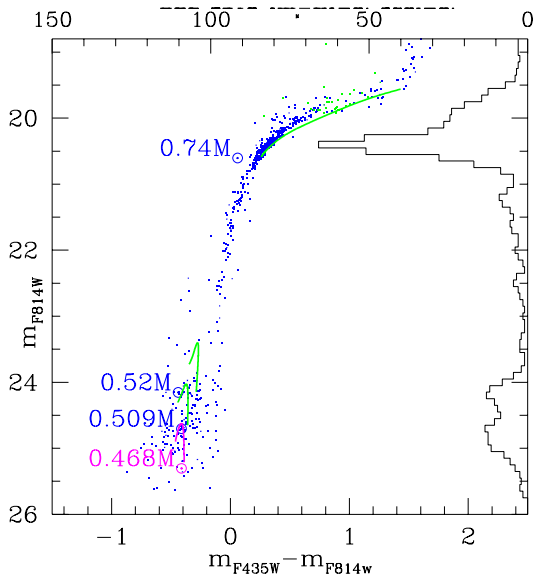


Figure 2. The HR diagram of the HB in the ACS data is shown. The histogram on the right shows the star number distribution versus magnitude m_{F814W} . Standard tracks of $M=0.74 M_{\odot}$, $M=0.52$ and $0.509 M_{\odot}$ for $Y=0.24$ and $M=0.468 M_{\odot}$ for $Y=0.42$ are overplotted.

sequently, different ages can be adopted, provided that the mass loss is consistently adjusted.

The RR Lyrae are identified as those stars that, in the simulation, belong to the T_{eff} interval $3.795 < \log T_{\text{eff}} < 3.86$. Their periods are computed according to the pulsation equation (1) by Di Criscienzo, Marconi & Caputo (2004).

Synthetic models for the RGB and for the turnoff region are computed according to the method described in Di Criscienzo et al. (2010).

We notice that all the evolutionary sequences have been translated from the theoretical Hertzsprung-Russell diagram (H-R) diagram to the observational CMD by using the color-Teff relation and bolometric corrections by Dotter et al. (2007). Obviously the synthetic spectra used for these computations do not represent accurately the peculiar atmospheres of hot flashers, because these stars are expected to have strongly enhanced He and C abundances at the surface. More in detail, for the atmospheres of hot flashers, Brown et al. (2001) have shown that an atmospheric composition of 96% He and 4% C (or N) produces lower fluxes in the F435W filter, compared to a standard metal mixture. Therefore, for the hot flasher model, one should use more appropriate- but not yet available- bolometric corrections, that however we do not expect to alter the basic conclusions of this analysis. As for the He-rich stellar population, Girardi et al. (2007) have shown that the effect of an enhanced He content- of the order of $\Delta Y \sim 0.1-0.2$ on bolometric corrections and colors is negligible at the Teff values corresponding to hot HB stars.

4 THE HORIZONTAL BRANCH

The HB of NGC 2419 has been analyzed in several recent studies (Ripepi et al. 2007; Sandquist & Hess 2008;

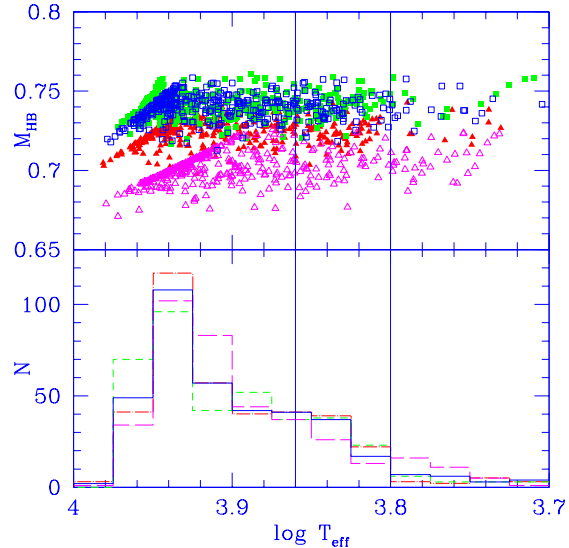


Figure 3. The top panel shows the distribution of the HB masses in the different simulations of the upper HB. The bottom panel gives the number distribution versus T_{eff} . Open squares and full line (blue): standard tracks; full squares, dashed line (green): OLDN14; full triangles, dot-dashed line (red): $\alpha 04$; open triangles, long-dashed line (magenta): D2002.

Dalessandro et al. 2008). We have now the possibility to examine further its characteristics, including in the study the full RR Lyrae catalogue described by Di Criscienzo et al. (2011). The HB is composed of two main parts: a luminous ($m_{F814W} < 21\text{mag}$) blue section, with a tail extension in the RR Lyrae and in the red part (UPPER HB), and the extreme HB (EHB) subluminal hot stars, defined here as the group at $m_{F814W} > 23.5\text{mag}$, that probably includes both the B subdwarfs at $T_{\text{eff}} > 20000\text{K}$, and the “blue hook” stars in the standard definition related to their appearance in the UV (Whitney et al. 1998; D’Cruz et al. 2000; Moehler et al. 2002). In the middle, these two parts are connected by a tail of intermediate luminosity stars (MIDDLE HB). The relative numbers in these three sections are given in Table 3. We point out that the UPPER HB and the EHB are the dominant components. In the following we use synthetic populations based on the models described above, in order to understand the main features of these two classes of objects.

4.1 The luminous part of the HB: a unique population with a small spread in mass

The histogram of the number of stars as a function of m_{F814W} in Fig. 2 shows that the upper HB is extremely peaked in color and in magnitude. This feature has been found also in M 53 (Rey et al. 1998), but not in other low metallicity clusters, such as M15 (Bingham et al. 1984), M68 (Walker 1994), and strongly suggests that this portion of the HB is populated by stars spanning a narrow mass range. Figure 3 shows the mass distribution obtained in our simulations as follows. For any choice of the evolutionary track set, a very small mass spread is sufficient to describe the peaked distribution in color (or T_{eff}). In fact, the RR Lyrae and red HB region, scarcely populated, are accounted for by

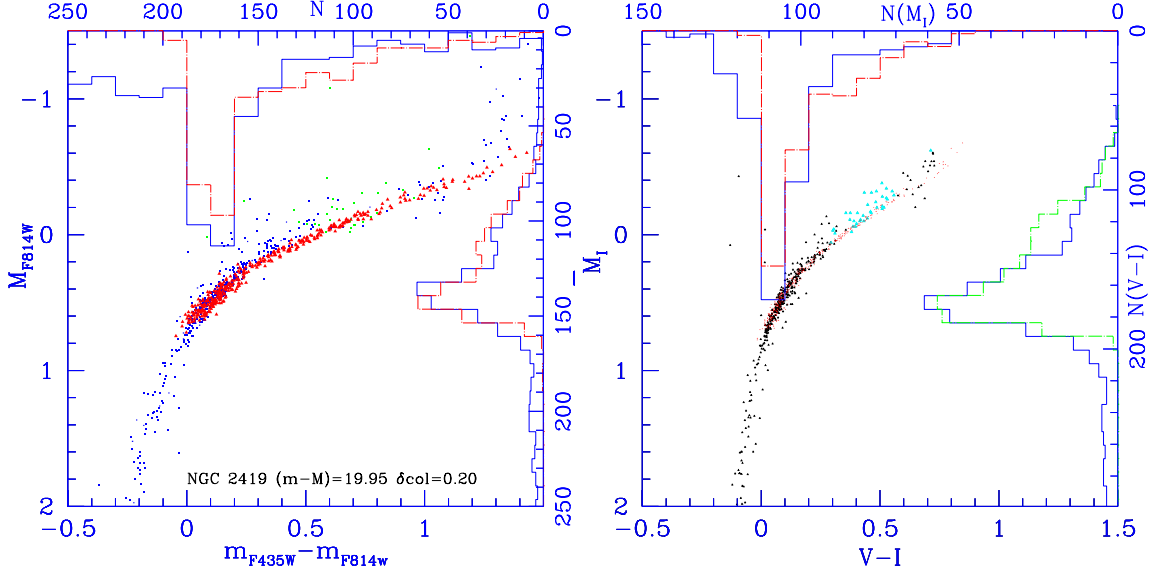


Figure 4. Simulation of the UPPER HB of NGC 2419 in the SUBARU magnitudes (left panel) and in the ACS magnitudes (right). In each figure the histograms of star counts as a function of the absolute magnitudes M_{F814W} or M_I and of the reddening corrected color $m_{F814W}-m_{F435W}$ or $V-I$ are compared to the histograms of the simulations. A small mass spread of $0.008 M_{\odot}$ has been assumed. Notice that the morphology of the tracks does not allow to account for the “blue tails”, unless we postulate an asymmetric mass loss. The assumed color excess (δcol) and the apparent distance modulus are also reported.

Table 3. HB counts

Range	SUBARU (obs) $r>50''$ $\chi<1.2$	ACS (obs) flag=1	ACS(corr) flag=1, $c>0.5, r>50''$	SH2008 (corr)	D’A2008 (corr)
UPPER ($M_I < 21$)	334	351	95	461	446
RR LYRAE	40	42	12	42	42
MIDDLE	70	80	30	130	53
EHB	61	160	74	363	257
TOTAL (N_{tot})	504	633	211	996	798
N_{EHB}/N_{tot}	0.12	0.25	0.35	0.36	0.34
BR(EHB)/BR(TOTAL HB)			0.27 – 0.31	0.27 – 0.31	

the late evolution of the masses starting their HB life near the peak in the star number distribution. Notice also that the evolution at these low metallicities remains close to the ZAHB for all the interested masses, even in the $Z=2 \times 10^{-4}$ models of D2002. The simulations for this UPPER HB are done both in the SUBARU and in the ACS magnitudes, whose data are described in Section 2. The panels in Figure 4 show some results for the standard tracks and for both set of data. We fixed the cluster age at 12 Gyr, at which the mass evolving in the red giant branch is $0.813 M_{\odot}$. An average mass loss of $0.073 M_{\odot}$ along the red giant phase then leads to an average mass of $0.74 M_{\odot}$ in HB. A small spread in mass ($\sigma=0.008 M_{\odot}$) is enough to provide a good fit of the UPPER HB, considering small observational errors in each magnitude of 0.01mag. Both the SUBARU (left panel) and ACS (right panel) data are reasonably fit³. The simulation

of the SUBARU data shows a larger number of RR Lyrae stars than found in the observations, possibly because the variable star catalogue is not yet complete. We did not investigate further this problem. In any case, we find that the period distribution of our RR Lyr sample can be satisfactorily interpreted in terms of a “tail distribution”, in the same way as the color distribution discussed above.

One interesting feature of these simulations is that we can not reproduce the extension of the HB towards fainter magnitudes, without adding hypotheses: any symmetric increase in the mass loss spread not only does not account for the long tail of stars at $m_I > 21$, but does no longer allow a good fit of the peak. The tail—that however concerns only a relatively small fraction of stars—may be ascribed to some asymmetry in the mass loss, or to a relatively small enhancement in the helium content of these few stars (see later). By changing the set of tracks (see Table2) in the simulations of the UPPER HB, the qualitative behaviour does not change. This part of the HB can still be interpreted as populated by the evolution of a small interval of masses, around the one which provides the fits of the peak in magnitude and color.

³ We recall that we have considered 40 RR Lyrae in the SUBARU sample (only those located at $r>50''$) and 42 variables in the ACS field. The numbers of HB stars in the two fields, obtained adopting the same selection criteria are reported in Table 2

Notice that a change in the cluster age does not necessarily require a change in the mass evolving on the HB, since a smaller (larger) mass loss along the RGB can be assumed for older (younger) ages.

The adopted metallicity (or exact elemental distribution) do change the evolving mass: e.g. the D2002 set ($Z=2 \times 10^{-4}$) needs an average mass loss of $0.113 M_{\odot}$, $0.04 M_{\odot}$ larger than the mass lost from the standard tracks (see Fig. 3)⁴.

4.2 The percentage of stars and the helium content in the EHB

In this work, we will not attempt to make precise fits of the EHB population, as the blue and near infrared bands that we are analysing are not the best on which to accomplish such a comparison, best performed in the ultraviolet bands (e.g. Brown et al. 2001; Lee et al. 2005; Brown et al. 2010). The aim of our simulations will be to understand, from the percentage of stars in this group, the relative birthrates of the UPPER HB and the EHB. According to our completeness analysis on ACS data⁵ described in Section 2.1.1, the EHB contains about 35% of the total HB stars. This is consistent with the value 36% obtained by Sandquist & Hess (2008) in their careful analysis, whose counts are reported in the fifth column of Table 3. The large fraction of stars rules out binary evolution for several reasons: 1) typical binary fraction in luminous GCs as NGC 2419 does not exceed $\sim 4\%$ (Milone et al. 2008); 2) observationally, no binaries have yet been found among the EHB stars (Moni Bidin et al. 2006, 2008); 3) in any case, the formation of B and O subdwarfs is a very peculiar and rare event in the binary evolution (e.g. Han et al. 2003); 4) the merging formation channel, that could be perhaps invoked in the dense core regions, is ruled out, as the EHB stars are distributed everywhere in the cluster within the tidal radius.

If the EHB is populated by stars having the same composition and age that we used for the UPPER HB, these stars have masses of $\sim 0.51 - 0.52 M_{\odot}$, whose location in ZAHB extends to the EHB region (see Figure 2). Consequently, the mass loss of $0.073 M_{\odot}$, that could account for the UPPER HB, must be increased to $\sim 0.3 M_{\odot}$. Notice that the standard HB lowest mass stars ($M \sim 0.506 M_{\odot}$, being the core mass at flash $0.505 M_{\odot}$) do not cover the lowest luminosities of the EHB. As we will see later, we can push these masses a bit further down, by including the location of models that have suffered a late-flash mixing (Brown et al. 2001; Cassisi et al. 2003; Brown et al. 2010), but the problem is not fully solved with “standard” models, and we prefer to attempt a different solution.

A dichotomy in the mass loss remains unexplained, so that we decided to test the case of similar mass loss for the EHB stars, but including a very helium rich composition for the progenitors, so that the total mass remnant after the helium flash is very small and lies at large T_{eff} (D’Antona et al. 2002). We assumed for the helium abundance in the EHB

stars a value $Y=0.42$. As we will see, the mass loss in the RG can not be kept exactly the same as for the UPPER HB, but must be increased by $\sim 0.035 - 0.05 M_{\odot}$ in order to reach the masses (and luminosities) of the EHB. We did not try to refine this result: a better correspondence between the mass loss in the UPPER HB and in the EHB can be obtained very easily by increasing the metallicity of the models (as discussed in Sect.4.1). We see that the lowest mass model of the $Y=0.42$ standard set ($M=0.468 M_{\odot}$) is much closer to the bottom magnitudes of the EHB, thanks to its smaller core mass.

Obviously, the choice $Y=0.42$ is a bold attempt to model the higher helium content of the EHB, and must not be regarded as a “precise” value. Notice, e.g., that this value is higher than the maximum helium contents of super-AGB stars ejecta (Ventura & D’Antona 2010; Siess 2010), the possible progenitors of a very helium rich second generation in GCs.

4.3 From the number ratio to the relative birthrates of EHB and UPPER HB stars

We will perform detailed simulations of the EHB stars in NGC 2419 with the aim to derive a reliable ratio of birthrates of the EHB and UPPER HB, from their number ratio. The simulations allow us to take into account both the different evolutionary times of the EHB stars, with respect to the UPPER HB, and the non-inclusion in the EHB of a possible percentage of helium rich stars that evolve directly to the white dwarf stage.

The relative birthrate of the EHB population, $\frac{BR_E}{BR_{\text{tot}}}$, can be written as:

$$\frac{BR_E}{BR_{\text{tot}}} = \frac{(1+f)N_E/t_E}{(1+f)N_E/t_E + N_M/t_M + N_U/t_U} \quad (2)$$

where E, U and M indicate the extreme, upper and middle HB, f is the fraction of stars that, due to mass loss, can not ignite the helium flash and evolves directly to helium white dwarfs. The t ’s represent the typical evolutionary times in each of the HB groups. The relation can be rewritten putting into evidence the timescales’ ratios:

$$\frac{BR_E}{BR_{\text{tot}}} = \frac{(1+f)N_E \times t_U/t_E}{(1+f)N_E \times t_U/t_E + N_M t_U/t_M + N_U} \quad (3)$$

Figure 5 shows the luminosity versus time evolutions of typical masses populating the HB: the 0.72 , 0.74 and $0.76 M_{\odot}$ standard track are taken as a reference. Comparison with one track computed with the old $^{14}\text{N}+\text{p}$ cross sections shows that the timescales do not change significantly. In the middle, the $0.509 M_{\odot}$ evolution, for $Y=0.24$, shows that the evolutionary times increases by $\sim 10\%$, while the evolution of 0.468 and $0.480 M_{\odot}$ for $Y=0.42$, evolving at the lowest luminosity, show an increase by $\sim 50\%$, and a bit more if we considere models representing the result of late helium flashers (see later on). Notice that the evolutionary times in HB depend very much on how semiconvection and/or overshooting are treated. In our case, models are computed by fixing to $\zeta=0.02$ our parameter for diffusive extra-mixing (see Sect.3), and we are implicitly assuming that the overshooting affects in a similar way both the UPPER HB and the blue hook models.

In order to have a reasonable idea about the factor f ,

⁴ We will see that this mass loss increase allows a better interpretation of the EHB as a group progeny of very helium rich progenitors.

⁵ We have excluded stars within $50''$ from the center, and having a value of completeness $< 50\%$.

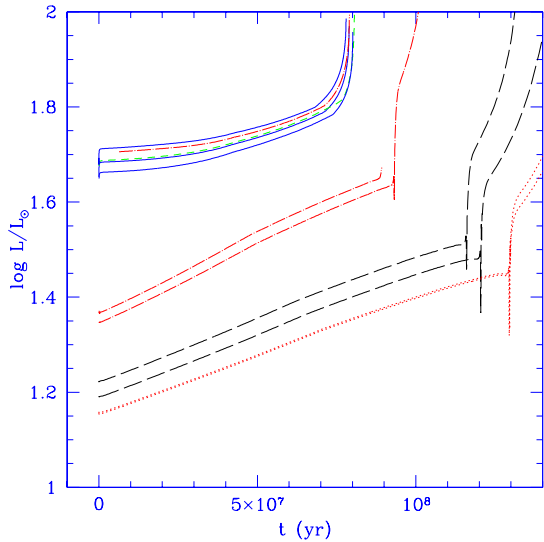


Figure 5. In the upper part of the figure time evolution of standard tracks of 0.72 , 0.74 and $0.77 M_{\odot}$ (continuous lines) plus $0.74 M_{\odot}$ OLDN14 (dot-dashed) and $\alpha04$ (short-dashed). Dot-dashed lines in the middle are the evolution of 0.509 and $0.52 M_{\odot}$ for $Y=0.24$ and dashed lines below are the 0.468 and $0.480 M_{\odot}$ for $Y=0.42$. Dotted lines at the bottom are the evolution of $M=0.460 M_{\odot}$ for $Y=0.8$ and $Y=0.9$ in the envelope.

we must make simulations, and discuss the hypotheses hidden in these simulations. Although the photometry is not as good as in other clusters, we can make the approximation that the EHB group is a mixture of HB stars progeny of giants that suffered an “early” late flash after leaving the RGB, plus stars that suffered a “late” late flash, and have been subject to deep mixing during this event (Brown et al. 2001). Which fraction of stars followed which path can be extracted from comparison between the simulations and the data. If we wish to simulate the late flash product, the limiting total remnant mass, following the late flash, is not the helium core mass reached at the flash occurring on the RGB (plus a few thousands of M_{\odot} in the hydrogen rich envelope), but is smaller, as the late flash can ignite at a smaller core mass. Following the few results in the literature (D’Cruz et al. 1996; Miller Bertolami et al. 2008) and our own preliminary computations (Ventura et al. 2010, in preparation), we put a limit at the minimum core mass for ignition of the late flash at $0.015 M_{\odot}$ below the core masses listed in Table 2. In order to simulate the late flash products, we compute models at these very low total masses by imposing that helium at the surface is increased to $Y=0.9$. In D’Antona et al. (2010) we proposed to fit the blue hook sequence in the cluster ω Cen by models with helium increased to $Y=0.8$, and showed that a very interesting reproduction of the “vertical” shape of the blue hook was possible. Nevertheless, the presence of carbon enhancement in the atmospheres of blue hook stars (Moehler et al. 2002, 2007) links them more closely to the result of flash mixing, so that this is the approach we follow in this work.

4.4 Simulations of EHB

Among the different possible hypotheses, we limit the discussion to the following cases:

- (i) the EHB is populated by stars having the same standard chemistry (Y and $[Fe/H]$) of the UPPER HB, but subject to larger mass loss on the RGB. The limiting mass is a bit smaller than the helium core mass at flash, $M_{min}=(0.505 M_{\odot}-0.015 M_{\odot})$, when this occurs on the RGB.
- (ii) the EHB is populated by stars with $Y=0.42$, and the minimum mass is fixed as in case (i), that is to $M_{min}=(0.466-0.015) M_{\odot}$;
- (iii) stars in the EHB follow the same path as in (ii), but the fraction with masses smaller than $0.468 M_{\odot}$ are considered “late flashers”, and their surface composition is considered to have been altered by deep mixing providing $Y=0.9$. No account is taken in the models of the probable carbon enrichment to 1–3%.

The last case corresponds then to the typical evolution in other clusters containing blue hook stars. Although our ACS sample is incomplete, we compare the simulations to the sample as it is, as we are interested particularly in obtaining a reliable description of the EHB sample luminosities, and in evaluating the possible number of “lost” helium white dwarfs, than in the completeness problems. We will use the corrected fraction of EHB stars (Table 3) when we will try to understand the relative birthrates. Therefore, a total number of 160–170 stars is assumed in the simulations. We fix the average mass lost on the RGB (δM) and its dispersion σ . We fix the limiting minimum mass, as discussed above, and any extraction ending with a smaller mass is rejected and accounted for as helium white dwarf. In the simulations we see that we need to lose a bit more than the $0.073 M_{\odot}$ taken to reproduce the UPPER HB, by 0.035 – $0.05 M_{\odot}$. We do not think that this is relevant, as we have seen that a slightly different choice of the input metallicity may allow us to require a bit larger mass loss for the UPPER HB, consequently reducing the discrepancy between the needed mass loss between the UPPER HB and the EHB.

Figure 6 shows one of the simulations corresponding to case (i). The (red) triangles and the dot-dashed histogram represent a simulation obtained for assuming a sample of stars with $Y=0.24$, mass loss $\delta M=0.309 M_{\odot}$ on the RGB, and $\sigma=0.01 M_{\odot}$. The limiting mass is assumed to be $0.509 M_{\odot}$ for the normal HB, and further the mass extraction is extended to $0.49 M_{\odot}$, assuming this as the limiting mass for the late helium flash. No mixing is included, so the hypothesis is quite conservative, but including models with mixing does not improve much the fit, as these models have too high a luminosity in any case. 102 helium white dwarfs are predicted by this simulation, a number that we can not consider realistic. If we attempt to reduce the number of helium white dwarfs by decreasing the average mass lost on the RGB, the simulated stars become too luminous with respect to the observed EHB sample. Notice that we can not change the distance modulus, that is obtained by fitting the UPPER HB. In Fig. 6, the MIDDLE HB is also simulated, by a separate simulation of standard composition stars with mass loss of $0.22 M_{\odot}$ and mass dispersion $\sigma=0.05 M_{\odot}$. It is not possible to reproduce in other ways these stars, neither by a simulation centered on the EHB,

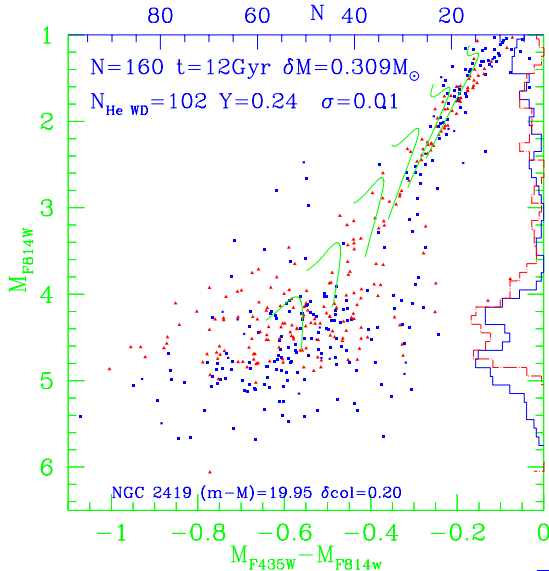


Figure 6. We show the HR diagram of the EHB in the ACS data, and the histogram of the number versus M_{F814W} distribution, together with the tracks of $Y=0.24$ and $M=0.509, 0.52, 0.54, 0.56, 0.58$ and $0.6 M_{\odot}$ from bottom to top. The simulation (triangles and dash-dotted histogram) is described in the text.

with larger mass spread, nor as an extension of the UPPER HB, as we discussed above.

Figure 7 shows an example of simulations for case (ii). The mass spread around the average value is taken to be $\sigma=0.006 M_{\odot}$. The total number of helium white dwarf of the simulation is only 9, namely $\sim 5\%$. Case (iii) is explored in Fig.8. The fit of the EHB sample is here very adequate, thanks to the inclusion of the dimmer (in the F814W band) points corresponding to the supposed flash-mixed stars. Notice that also in this case the number of helium white dwarfs is predicted to be zero.

Other simulations predict a larger number of helium white dwarfs, depending on the assumed mass loss dispersion assumed. Independently from the observational incompleteness, we stress that the blue hook progenitors are probably within a maximum $\sim 20\%$ more than the EHB sample.

The simulations show that *the EHB is better simulated including the presence of a large population with enhanced helium*. We can now go back to Equation 3, including the number ratios of Table 3 by Sandquist & Hess (2008), f between 0 and 0.2, assuming also $t_E/t_U=1.56$, $t_M/t_U=1.13$ from the models. If we consider the cluster “second generation” to be limited to the EHB sample, the birthrate of this population is between 27 ($f=0$) and 31% ($f=0.2$) of the total cluster population. If we include the MIDDLE HB in the second generation, the figures increase to 40 – 44% of the total. The MIDDLE HB however does not reach the very high helium contents required for the EHB sample.

We now examine the other HR diagram features to understand whether this conclusion is consistent with the information derived from the RGB and MS.

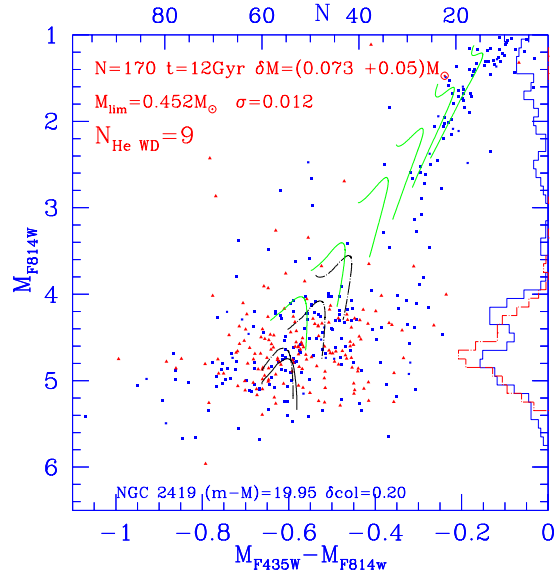


Figure 7. As in Fig.6, the ACS data are compared to a simulation that assumes $Y=0.42$ for the EHB stars. In addition to the $Y=0.24$ tracks shown also in Fig 6, three tracks for $Y=0.42$ and $M=0.468, 0.480$ and $0.5 M_{\odot}$. The lowest track is for $M=0.452 M_{\odot}$ (core mass $0.45 M_{\odot}$). The dot-dashed histogram represents the simulation described in the text, that assumes an average mass loss $\delta M=0.123 M_{\odot}$ on the RGB, and $\sigma=0.006 M_{\odot}$. 9 helium white dwarfs are predicted by the simulation.

5 THE INTRINSIC BROADENING OF THE BASE OF RGB

In order to confirm the suggestion that the blue hook stars are enhanced in helium, we analyze the stars along the red giant branch, where a large He enhancement manifests itself as a RGB split, or as a spread in a well populated CMD. Theoretical predictions (e.g. Catelan et al. 2010) show that the base of RGB of He-enhanced models is hotter than their lower – helium counterparts, by about $\Delta(B-I)/\Delta Y=-0.7$. For the case explored here ($\Delta Y=0.18$), this spread is larger than the observational errors for both our data sets (SUBARU and HST). The size of the predicted split/spread decreases progressively towards the RGB tip, where the presence of AGB stars may also complicate any empirical test. Consequently, we restrict our analysis to the interval in apparent magnitude in between the base of RGB and $m_{F814W} \sim 19$ mag.

The main challenge in identifying intrinsic spreads in the colors of the RGB, comes from the fact that photometric errors can generate similar signatures. Anderson et al. (2009) have introduced an efficient approach to distinguish intrinsic color broadening from mere photometric errors that consists in analysing different data sets and see if all of them share the same features. The large amount of ACS/WFC archive images of NGC 2419 (see Table 1) give us the precious opportunity to follow a similar procedure for this cluster. Specifically, we made three independent CMDs by using images in six passbands: i) m_{F435W} and m_{F814W} , ii) m_{F475W} and m_{F850LP} and iii) m_{F555W} and m_{F775W} .

The m_{F435W} vs. $m_{F435W}-m_{F814W}$ CMD is shown in Fig. 9a. The wide color baseline of this CMD provide an optimal resolution of any doubling or spread of the observed

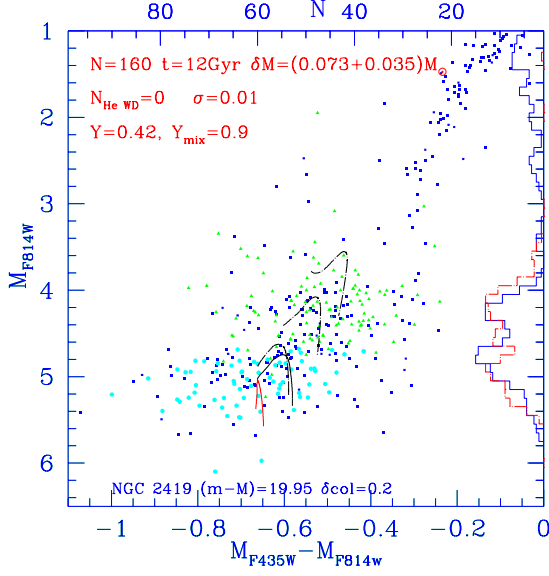


Figure 8. As in Fig. 7, but the simulation now includes 100 stars with $Y=0.42$ (triangles), plus 70 stars supposed to have undergone flash mixing, having $Y=0.9$ (dots). In addition to the four tracks $Y=0.42$, the mass 0.46 for $Y=0.9$ is shown (last on the bottom left). No helium white dwarfs are predicted by the simulation.

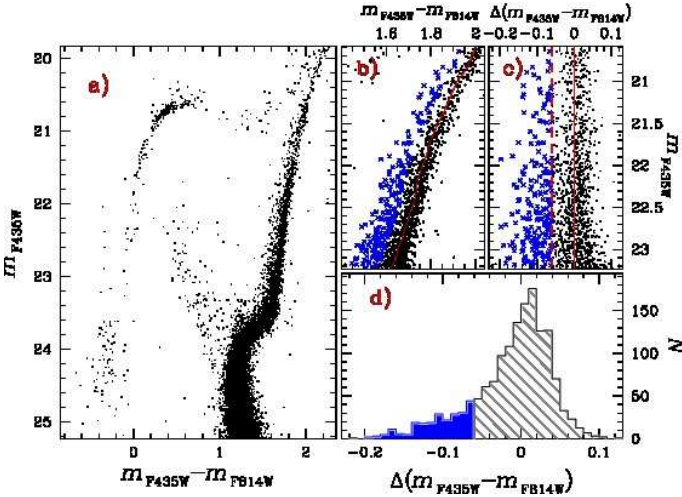


Figure 9. a) m_{F475W} vs. $m_{F475W} - m_{F814W}$ CMD from ACS/WFC data b) and a zoom around the RGB region. Panels c) and d) show the analysis performed to put into evidence the spread of the RGB in the way described in the text.

sequences due to helium variations. A visual inspection of this CMD immediately suggests that NGC 2419 has a broad RGB with the presence of a tail of stars blueshifted with respect to the main RGB population.

To further investigate this suggestion in the *Panel b)* we show a zoom of the CMD around the RGB region where the color spread is more evident. The red continuous line is the RGB fiducial obtained by following the recipes given in Milone et al. (2008). Briefly, we have divided the RGB into intervals of 0.2 magnitudes in the F435W band, calculated the average color and magnitude for each of them,

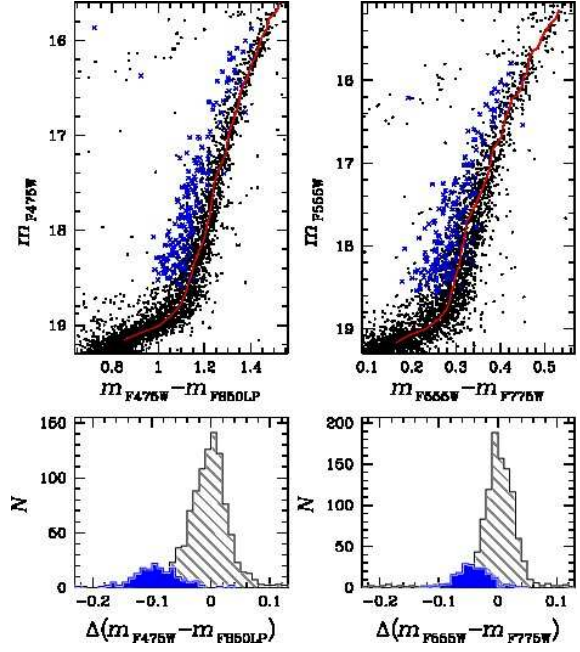


Figure 10. In order to show that the RGB broadening is intrinsic we compare the CMD of Fig. 9 with CMDs from two other data sets (see Table 1). Upper panels are the CMDs zoomed around the RGB and the (blue) cross identify stars selected as "blue" in the previous Fig. 9. Lower panels show the color distributions in these new colors. The fact that the histogram distributions of the selected blue stars systematically have bluer colors demonstrates that the RGB broadening is intrinsic.

and interpolated these points by means of a spline. In *Panel c)* we have subtracted from the color of each star the color of the fiducial at the corresponding magnitude and plotted m_{F435W} as a function of the obtained color difference ($\Delta m_{F435W} - m_{F814W}$). The histogram color distribution plotted in the *Panel d)* is clearly skewed towards blue colors and we have arbitrarily isolated RGB stars with $\Delta m_{F435W} - m_{F814W} < -0.06$. These stars have been represented as blue crosses in the *Panels b)* and *c)*.

We note that if the RGB broadening is due to photometric errors alone, a star that is bluer than the RGB fiducial in the m_{F435W} vs. $m_{F435W} - m_{F814W}$ CMD have the same probability of being bluer or redder in other CMDs obtained with independent data. But if the color spread is real the selected blue stars will have bluer colors in all the CMDs. In Fig. 10 we compare the CMD of Fig. 9 with CMDs from two other data sets. Upper panels are the CMDs zoomed around the RGB. Each (red) line is the RGB fiducial obtained with the method described above and we have kept for each star the same color that it had in Fig. 9. Lower panels show the color distributions. The fact that the histogram distributions of the selected blue stars systematically have bluer colors demonstrate the the RGB broadening is intrinsic. We now can consider this evidence as the consequence of a population in the cluster with an enhanced primordial helium. A quantitative comparison is done by performing simulations able to reproduce the color distribution. Population synthesis follows the outline described in Ventura et al. (2009). A good match is obtained by assuming a sample of 70% of stars with primordial

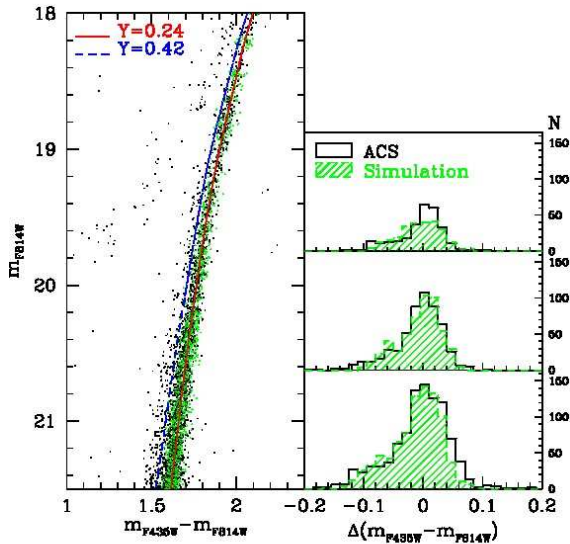


Figure 11. Zoom of the CMD region at the base of RGB from ACS data together with our best simulation (see text). (Right panels) Distribution of the difference between the color of each star and the averaged Ridge Line calculated for this part of RGB calculated in three different interval of magnitude (solid histogram) which highlights the intrinsic broadening of the data well reproduced by our simulation (dashed-shaded histogram) made up of 30 % off stars with $Y=0.42$ and the rest with primordial helium abundance.

helium abundance and 30% of stars with $Y=0.42$, if we assume $\sigma_{obs}=0.018\text{mag}$ (see Fig. 11). This assumptions are compatible with the observational errors of the ACS/HST data and the simulations can reproduce both the width and the shape of distribution.

On the contrary, Fig.12 shows that a single population with fixed $Y=0.24$, is not able to reproduce the observed population, especially in the faintest magnitude interval. To quantify this statement in Fig. 13 we show the cumulative distributions of the color differences ($\Delta m_{F435W} - m_{F814W}$); the results of the comparison between the distributions using a K-S test are also listed which show that the agreement between observations and simulations is better if we assume a double population.

If we could reduce the observational errors, the split of the two RGBs would be observable for $\sigma_{obs}=0.01\text{ mag}$ in the same colors at least at the base of RGB; at the distance of NGC 2419 this will be possible when the next generation telescopes (e.g E-ELT or JWST) will be available.

We note that in the case of NGC2419 that population that we recognize as the second generation is bluer on RGB than the primordial one, contrary to what happens for other clusters which shows evidences of multiple populations, in particular M4 (Marino et al. 2008) and NGC6752 (Milone et al. 2010) where Na rich stars are cooler than Na poor ones.

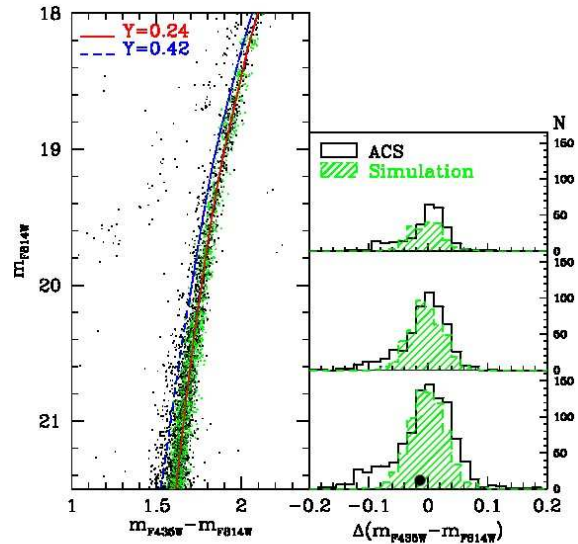


Figure 12. The same as Fig. 11, but in this case the simulation includes only stars with primordial helium content ($Y=0.24$).

We interpret this evidence as the consequence of the strong He enhancement found for the SG stars which, at the low metallicities of NGC2419, prevails on the effects of light element abundances (such as Na enhancement, or O depletion).

6 THE MAIN SEQUENCE

Sandquist & Hess (2008) have ruled out the hypothesis of a very high initial helium abundance ($Y \sim 0.4$) for blue hook stars, mainly by noticing that the distribution in color of the MS stars from their data resemble a Gaussian distribution and does not show any asymmetry which would arise from the presence of 30 per cent of He-rich stars. The symmetry of the MS is confirmed by both our data sets where no bi-modal main sequence nor any noticeable asymmetry of the distribution emerge; however our simulations show that the observational errors of our data, which increase with magnitude, may be able to cancel any color shift. To explain this point in Fig. 14, we also show that the data are perfectly matched with a synthetic population formed by 30 % of stars with $\Delta Y=+0.18$ with respect the main population.

In conclusion we notice that although Sandquist & Hess (2008) limit a maximum ΔY among the cluster stars to <0.05 , this value is derived from the ratio $R=N_{HB}/N_{RG}$ where N_{RG} are the giants above the HB level and not from the broadness of the MS. As well known, this ratio is not a sensitive helium indicator, if the horizontal part of the HB corresponds to the luminosity level of standard helium stars (see also Caloi & D'Antona, 2007). This is in fact the case

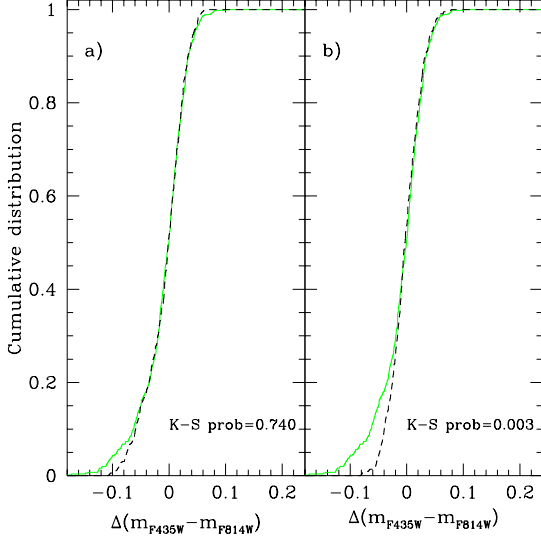


Figure 13. Cumulative distributions of $\Delta(m_{F435W} - m_{F814W})$ from observed (dashed lines) and simulated (solid lines) stellar components computed from (a) two populations with $\Delta Y=0.18$ and (b) a single population with fixed $Y=0.24$. The results of the comparison between the distributions using a K-S test (K-S prob) are also labelled.

for NGC 2419, where helium rich stars are only those in the EHB.

7 CONCLUSIONS AND DISCUSSIONS: WHY TWO POPULATIONS?

The fundamental result of this work is the following: in contrast with previous results, we have built a well founded case for the presence of two different stellar populations in NGC 2419, distant massive GC, now well isolated from the tidal influence of the Galaxy. The first stellar population is identified with the UPPER HB including the luminous blue stars, the RR Lyrae stars and the few red HB stars. These have a normal He abundance and are easily interpreted as the result of the evolution of a small range of initial stellar masses in ZAHB. The second stellar population represents 30 per cent of the total cluster stellar population and is identified with the EHB possibly subdivided into a B-subdwarf part plus a blue hook, that we fit with models having initial helium content $Y=0.42$ and being subject to a mass loss very similar to the mass loss required for the UPPER HB. The value $Y=0.42$ is not mandatory, as a different, larger, choice of the initial $[\text{Fe}/\text{H}]$ may allow a fit with a smaller (but in any case very high) helium. The MIDDLE HB may be part of the helium enriched population –but with a much smaller helium enhancement– or may be attributed to a tail of larger mass loss along the RGB,

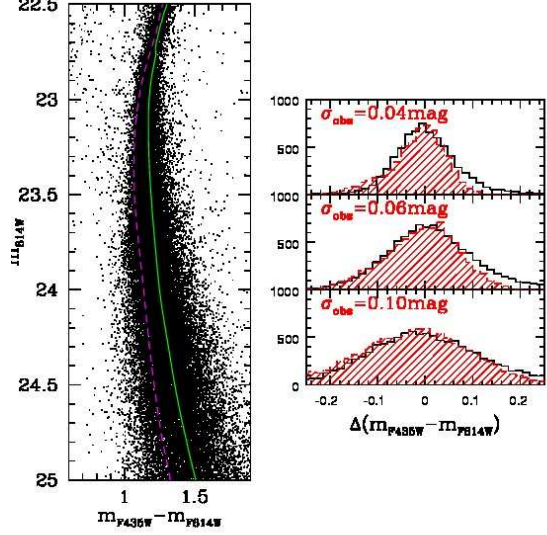


Figure 14. Same as Fig. 11 but for three different bins in magnitude on the Main Sequence. The solid and dashed lines in the left panel refer to the isochrones calculated for $Y=0.24$ and $Y=0.42$ respectively. The observational errors reported in each box and included in the simulations reproduce the enlargement of σ_{obs} going to fainter magnitudes.

in standard helium stars. In the most conservative case (only the EHB is helium rich), we conclude that 27–30% of the cluster stars are born from a “second generation” very helium rich gas.

It is now interesting to discuss the implications of the results presented in this paper for the initial properties of NGC2419 and its subsequent dynamical history.

According to the models presented in D’Ercole et al. (2008, 2010), the Extreme population must have formed early in the SG formation process directly out of the pure ejecta of massive AGB stars without any dilution with pristine gas. For example, in D’Ercole et al.’s (2010) model for NGC 2808 (a massive cluster with a significant fraction of E stars), the Extreme population observed in this cluster would have formed in the time interval 31.7–44 Myr from the AGB ejecta of stars with masses in the range $7.5\text{--}9 M_{\odot}$.

If we assume that the Extreme population of NGC 2419 was also formed from the ejecta of stars in this same range of masses and adopt a Kroupa-1993 IMF (Kroupa et al. 1993), the total amount of gas lost by these massive AGB stars is $M_{\text{ej}} = 0.01 M_{\text{FG},i}$, where $M_{\text{FG},i}$ is the initial GC mass, composed exclusively by FG stars. From the observational results presented in this paper, we can write $M_{\text{SG},E} = 0.3 M_{\text{GC}}$, where $M_{\text{SG},E}$ is the mass of the Extreme population, and M_{GC} is the present GC mass. Assuming that all the AGB ejecta is exhausted by the star

formation, and that no substantial loss of SG stars is suffered by the cluster during its successive dynamical evolution, we obtain $M_{\text{SG}} = 0.01M_{\text{FG},i} = 0.3M_{\text{GC}}$ and, in the end, $M_{\text{FG},i} = 30M_{\text{GC}}$. If a Kroupa-2001 IMF (Kroupa 2001) is adopted, the larger fraction of the total cluster mass contained in stars within the range 7.5-9 M_{\odot} leads to $M_{\text{FG},i} \simeq 15M_{\text{GC}}$. These computations show that for any choice of the IMF, NGC2419 lost a larger amount of its original mass than "normal" Galactic GCs, even up to 97 per cent.

The above conclusions are not surprising as a few more massive clusters found to host E stars also have a spread of heavy elements and must have been initially more massive by a similar large factor (see e.g. Renzini 2008). However the unusual relative number of Extreme and Intermediate stars in NGC 2419 is likely to be the result of a peculiar SG formation history. Specifically, the lack of a significant fraction of an Intermediate SG population suggests that the SG formation episode was interrupted earlier before the ejecta of AGB stars with $M < 7 M_{\odot}$ could be converted into SG stars. This is at odds with the ubiquitous presence of a large fraction of Intermediate SG stars found in all the other clusters that have been studied with spectroscopic observations (see e.g. Carretta et al. 2009a).

The peculiar star formation history suggested by the results presented in this paper might be connected to the cluster early dynamical evolution. Unfortunately, without any information on the orbit of NGC 2419 and the properties of the tidal environment in which this cluster was embedded during the very early stages of its evolution, it is difficult to build a model of the early dynamical processes behind the interruption of the SG formation event and the mass loss this cluster must have suffered.

At its current galactocentric distance ($R_g \sim 90\text{kpc}$; Harris 1996, 2010 edition), the Jacobi radius of NGC2419 determined by the strength of the Galactic tidal field at R_g is $r_J \sim 700$ pc. Considering that its estimated King truncation radius is $r_t \sim 220$ pc and its half-mass radius is $r_h \sim 30$ pc, one could infer that NGC2419 must be the prototype of a cluster evolving in isolation and which, therefore, should not have been able to lose any AGB ejecta or stellar mass. However one can easily envisage a number of conditions leading to a significantly different early dynamical history affecting both the gas and the stellar content. Assuming, for example, the cluster was on an eccentric orbit with pericenter at 11 kpc, as suggested by Casetti-Dinescu et al (2009) (see also the discussion in Cohen et al. 2010), it is possible that an early tidal shock event and/or a cluster early expansion (triggered by primordial gas and SN ejecta expulsion as discussed in D'Ercole et al. 2008) in a stronger tidal field might have affected the SG formation process and caused the loss of a significant fraction of the initial FG mass.

Another possibility is that NGC2419 was located, during the early stages of its evolution, in the inner regions of a dwarf galaxy and therefore subject to a stronger tidal field than it is now; also in this case the early expansion phase as modeled in D'Ercole et al. (2008) might have led to a strong FG loss. Indeed, Newberg et al. (2003) suggested that NGC 2419 might have been once part of the Sagittarius galaxy (see, however, Law & Majewski, 2010 for a recent discussion of this possibility).

Although only additional studies on the stellar population

and on the orbital properties of NGC2419 will allow to better constrain its dynamical and star formation history, our results give further support to previous suggestions (van den berg & Mackey 2004, Mackey & van den bergh 2005, Cohen et al. 2010 and very recently Bruns & Kroupa 2011) that NGC2419 must be the remnant of a much more massive system.

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